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ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF OUTFLOW RESIDUALS IN INTERCONNECTED SPHERICAL TANKS

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ABSTRACT

An analysis is presented for predicting the propellant distribution during outflow of multiple-interconnected spherical tanks for possible space vehicle application. Analytical and experimental data are presented for four spherical tanks using water as the working fluid. The effects on final liquid residuals were determined for tanks that: (1) did or did not utilize crossflow lines between tanks for liquid level equilibration, (2) were initially equally or unequally loaded, and (3) had equal or unequal length outflow lines. The analysis adequately predicted the experimental residuals as well as the point at which crossflow lines ceased to be effective equilibration flow paths.

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SUMMARY

An analytical and experimental investigation was conducted to determine liquid residuals when outflowing four equal volume interconnected spherical tanks. The effects of outflow rate and unsymmetrical initial liquid loading among tanks on final liquid residuals were examined. Water was used as the liquid, and a pumped expulsion rather than expulsion by ullage pressure was used to outflow the tanks. Three different configurations, each of which included the use of crossflow lines, were investigated. The equations used to predict the amount of liquid in the tanks as a function of time are presented along with a comparison of the analytical and experimental results. An example of the application of the analysis to predict residuals and crossflow line size for a flight vehicle is presented.

INTRODUCTION

Vehicle length is an important consideration in the design of upper stages of launch vehicles and extraterrestrial landing stages. Minimizing the height of these stages can affect mission performance by reducing, for example, launch vehicle bending moment and landing gear size. Incorporating multiple fuel tanks and/or multiple oxidizer tanks is one method of reducing overall stage height.

When multiple propellant tanks are used in a propulsion system, there may be a difference in fluid residuals remaining in the tanks at cut-off due to a difference of individual pressure drops in the respective outflow lines. In addition, propellant transfer can occur between tanks as a result of unsymmetrical heating during prolonged zero "g" coast or as a result of a low "g" vehicle orientation maneuver. In a two-burn mission, redistribution of the propellant between tanks could cause a premature gas blow-through shutdown if some provision is not made for equalizing the fluid distribution among tanks. Crossflow lines, which are investigated analytically in reference 1, are a potential solution to this problem.

Crossflow lines are low flow velocity interconnecting lines joining the individual tanks of a multiple tank system. They are independent of the higher flow velocity outflow lines and, hence, provide clean paths for equilibration flow between tanks. This becomes particularly important when outflow lines are of unequal length or when the liquid volume is different in each tank. The crossflow line may be attached directly to the bottom of the tank or to a sump that is an integral part of the tank. The advantage of using a sump is that it allows the tank to be completely emptied. A sump is effective if the lower central pressure produced by the inward acceleration associated with draining to a center outlet does not result in blow-through before the liquid level has reached the sump. Under normal gravity conditions, body forces act to smooth out the liquid surface depression that results from this inward acceleration. Under zero gravity conditions, only the relatively weak surface tension forces remain to prevent the liquid from being removed in a central core. The formation of vortex flow can also result in premature blow-through. Experiments with baffles at the outlet have indicated that such devices can be used to help minimize these problems (ref. 2).

The primary purposes of this report are to present a theoretical analysis for predicting liquid residuals in multiple tank systems with or without crossflow lines and to compare the analysis with experimental data. Examples illustrating the application of the analysis are presented. In addition, analytical and experimental results are presented for three configurations involving various outflow line arrangements and unequal initial liquid volumes. An example of the applicability of the analysis to the propellant system of a hypothetical stage is presented in appendix B.

ANALYSIS OF LIQUID OUTFLOW FROM SPHERICAL TANKS

Purpose

In designing a stage employing multiple tanks with crossflow lines, it is desirable to determine the relation between tankage and line characteristics and fluid residuals so that the smallest line size that will accommodate expected fluid equilibration requirements can be selected. The analysis included herein provides a means for predicting the amount of liquid in each propellant tank of a multiple tank system during outflow with and without crossflow lines. The liquid volume in each tank at the beginning of the expulsion phase can be equal or unequal depending on the initial conditions.

Although the primary purpose of the experimental data was to verify the analysis, an attempt was made to simulate outflow conditions of a liquid oxygen system on a typical vehicle by using a water flow rate of 13.9 pounds per second (6.31 kg/sec) or

100 gallons per minute (0.0063 m^3/sec) for a majority of the experimental runs. This typical vehicle stems from studies made of multiburn high energy upper stages employing multiple oxidizer tanks and experiencing an average 4-g acceleration during the second burn. In order to approach complete dynamical similarity, the Froude number and Reynolds number should be the same for both the vehicle and test model. However, in this case, since the effects of viscosity on the flow are small compared to those of gravity, Reynolds number similarity between the model and vehicle was neglected. Therefore, the model flow rate of 13.9 pounds per second (6.31 kg/sec) was arrived at by Froude number considerations only.

Equations and Assumptions

The rate of change in the amount of liquid in the j^{th} tank is given by

$$\left(\frac{dm}{dt}\right)_j = \sum_{i=1}^{N_j} \dot{m}_{ij} - \dot{w}_j \tag{1}$$

where $(dm/dt)_j$ is the rate of change in the mass of liquid in the j^{th} tank; $\dot{m}_{ij}$ is the rate at which liquid enters the j^{th} tank through the crossflow line connecting the i^{th} and j^{th} tanks; $\dot{w}_j$ is the mass flow rate from the j^{th} tank through the outflow lines; and N_j is the number of crossflow lines connected to the j^{th} tank. (Additional symbol definitions may be found in appendix A.)

Assuming the liquid to be incompressible gives

$$\left(\frac{dm}{dt}\right)_j = \rho\left(\frac{dv}{dt}\right)_j$$

When the propellant tanks are restricted to geometries for which the rate of change in liquid volume is dependent on only one variable (y), the rate of change in liquid volume can be expressed as

$$\frac{dv}{dt} = \frac{dv}{dy}\frac{dy}{dt}$$

Equation (1) for the j^{th} tank can be rewritten as

$$\left(\frac{dv}{dt}\right)_j = \frac{\sum_{i=1}^{N_j} \dot{m}_{ij} - \dot{w}_j}{\rho\left(\frac{dv}{dy}\right)_j} \tag{2}$$

The crossflow line meets each of the two tanks it connects at the lowest point of each tank. For a spherical tank,

$$v = \pi(ry^2 - y^3/3)$$

and

$$\frac{dv}{dy} = \pi(2ry - y^2) \tag{3}$$

where y is the vertical height of the liquid surface above the bottom of the tank, and r is the radius of the tank.

The relations for the liquid volumes as a function of vertical height for other tank geometries are given in reference 1.

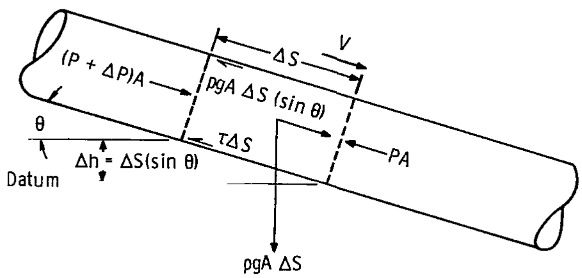
Combining equations (2) and (3) for a spherical tank gives

$$\left(\frac{dy}{dt}\right)_j = \frac{\sum_{i=1}^{N_j} \dot{m}_{ij} - \dot{w}_j}{\rho\pi(2ry - y^2)_j} \tag{4}$$

From the continuity equation,

$$\dot{m} = \rho AV \tag{5}$$

The equations which determine the velocity are given in reference 3. The flow is assumed to be one dimensional and each line has a constant cross section. The following sketch shows a force balance for an element of fluid in a crossflow line and can apply to an element in an outflow line as well.



The equation for the force balance on the element in the axial direction is

$$(P + \Delta P)A - PA + \rho g A \sin\theta\ \Delta S - \tau \Delta S \mathscr{P} = \rho A\ \Delta S\ a \tag{6}$$

The shear stress at the wall is taken to be proportional to the velocity squared:

$$\tau = f\rho \frac{V^2}{2} \tag{7}$$

For circular tubes, $\mathscr{P} = \pi D$ and $A = (\pi/4)D^2$. When equation (6) is rewritten and both sides are divided by A, the result is

$$\Delta P + \rho g \sin\theta\ \Delta S - 4f\left(\rho \frac{V^2}{2}\right)\frac{\Delta S}{D} = \rho\ \Delta S\ a \tag{8}$$

The acceleration (a) can be written as

$$a = \frac{dV}{dt} = \frac{\partial V}{\partial S}\frac{dS}{dt} + \frac{\partial V}{\partial t}\frac{dt}{dt}$$

For tubes of constant cross section $\partial V/\partial S = 0$. It is assumed that all lines are full at the beginning of outflow. The inertia forces are neglected so that the quasi-steady state solution is found. It seems reasonable to do this since the velocities in the lines are not large. Therefore, the net accelerations are small. Also, in practice, line lengths would be kept to a minimum. Therefore, the mass of fluid in the lines would be small. With this combination, the term on the right-hand side of equation (8) can be neglected.

The integration of equation (8) from the beginning of the line to the end gives

$$\int_{P(0)}^{P(L)} dP + \int_0^L \rho g \sin\theta \, dS = \int_0^L \frac{4f}{D} \frac{\rho V^2}{2} dS \tag{9}$$

For the crossflow line connecting the i^{th} and j^{th} tanks, P(L) is the static pressure at the base of the i^{th} tank ($P(L) = P_i$); and P(0) is the static pressure at the base of the j^{th} tank ($P(0) = P_j$).

Carrying out the integration of equation (9) for the crossflow line gives

$$P_i - P_j + h_{ij}\rho g = \left(\frac{4f_{ij}L_{ij}}{D_{ij}}\right)\frac{\rho}{2} V_{ij}^2$$

where it is assumed that the acceleration acts in the vertical direction, and h_{ij} is the vertical height between the i^{th} and the j^{th} tanks.

In addition to the friction loss, there may be other nonrecoverable head losses. These would be incurred by exits, entrances, and fittings. These losses are referred to as "minor" losses in the literature. However, they may be the most significant ones when the connecting tube lengths are relatively short. The sum of these nonrecoverable head losses is also assumed to be proportional to the velocity squared. Incorporating this term into the above equation gives

$$P_i - P_j + h_{ij}\rho g = \left(\frac{4f_{ij}L_{ij}}{D_{ij}} + K_{ij}\right)\frac{\rho}{2} V_{ij}^2 \tag{10}$$

where K is the sum of the loss coefficients in the line excluding friction.

It is assumed that the flow through the crossflow lines does not interact with the flow through the outflow lines. Also the effects of the fluid velocities inside the tanks are neglected. Hence, the static pressure at the base of the i^{th} tank is

$$P_i = P_{oi} + \left(y_i - \frac{V_{ij}^2}{2g}\right)\rho g$$

and for the j^{th} tank it is

$$P_j = P_{oj} + \left(y_j - \frac{V_{ji}^2}{2g}\right)\rho g$$

Since $|V_{ij}| = |V_{ji}|$, the velocity in the crossflow line is

$$|V_{ij}| = \frac{\sqrt{|P_{oi} - P_{oj} + \rho g(S_{ij} \sin \theta_{ij} + y_i - y_j)|}}{\sqrt{\frac{\rho}{2}\left(\frac{4f_{ij}L_{ij}}{D_{ij}} + K_{ij}\right)}} \tag{11}$$

If the pressure above the liquid is the same for each tank, then $P_{oi} = P_{oj}$, and the velocity in the crossflow line is independent of tank pressure. The absolute pressure in the crossflow line, however, is dependent on the tank pressure.

If the term under the radical in the numerator of equation (11) is positive before the absolute value is taken, V_{ij} is positive and flow is from the i^{th} tank to the j^{th} tank. If it is negative, then V_{ij} is also negative and liquid flows from the j^{th} tank to the i^{th} tank.

The total flow rate from all the tanks $(\dot{m}_T)$ is known as a function of time. The flow rate through the outflow line of each tank $(\dot{w})$ is determined by pressure and mass balances in the outflow lines. Since the pressure at a junction of two or more outflow lines is a function of the piping arrangement, the pressure balances are presented for three different example piping systems.

Case I. - In this case, which is illustrated in figure 1, all of the tank outflow lines meet at a common junction. Then,

$$\dot{m}_T = \sum_{j=1}^{M} \dot{w}_j \tag{12}$$

where M is the number of outflow lines and is equal to four in this case.

From the continuity equation,

$$\dot{w}_j = \rho A_{jc} V_{jc}$$

where A_{jc} is the cross sectional area of the line connecting the j^{th} tank to the junction, and V_{jc} is the fluid velocity in this line.

Let P_c be the total pressure at a nearby point downstream of the junction. This pressure is a function of the line losses in each of the outflow lines. Expressed in terms of the losses in the line from the j^{th} tank, P_c is written as

$$P_c = P_j + \rho g h_{jc} - \left(\frac{4fL}{D} + K - 1\right)_{jc} \frac{V_{jc}^2 \rho}{2} - H_{jc} \rho g \tag{13}$$

where h_{jc} is the difference in elevation between the base of the j^{th} tank and the junction; and H_{jc} is the head loss due to mixing when the outflow lines join together into a common line. It is convenient to express H_{jc} as $K'_{jc}(V_{jc}^2/2g)$ where K'_{jc} is the loss coefficient associated with the head loss due to mixing. A method for estimating the head loss due to mixing is given in reference 4. The analysis in this reference, however, is concerned with the situation where there are only two lines joining into a common line. For each of the experimental configurations investigated herein, there were four outflow lines joined into a common line. Care was taken to have all of these lines enter tangentially into the common line. Furthermore, the sum of the cross sectional areas of the outflow lines was approximately equal to the cross sectional area of the common line. Therefore, mixing without loss was generally assumed. It is shown in a subsequent section of this report that the analytic liquid residuals for the experimental configurations were relatively insensitive to the value of the mixing loss coefficient.

The static pressure in the outflow line at the base of the j^{th} tank is

$$P_j = P_{oj} + \rho g y_j - \frac{V_{jc}^2 \rho}{2} \tag{14}$$

Combining equations (13) and (14) gives

$$P_c = P_{oj} + \rho g(y_j + h_{jc}) - \left(\frac{4fL}{D} + K + K'\right)_{jc} \frac{V_{jc}^2 \rho}{2} \tag{15}$$

Since P_c has the same value when calculated using any of the lines leading to the junction, there are M equations of the same form as equation (15). These M equations plus equation (12) are used to calculate the velocity and, hence, the mass flow rate in each outflow line. This in turn gives the total pressure near the junction.

Case II. - In this case, illustrated in figure 2, only two tanks have outflow lines that meet at a common junction. The other two tanks do not have outflow lines and must outflow through the crossflow lines. The equation for the mass flow rate through the outflow lines is

$$\dot{m}_T = \sum_{j=1}^{Q} \dot{w}_j \tag{16}$$

where Q is the total number of outflow lines and is equal to two for this case. Q equations of the form of equation (15) are used together with equation (16) to find the mass flow rates in the outflow lines. The M minus Q tanks that do not have outflow lines empty through the crossflow lines and the rate at which they empty is determined by equations of the same form as equation (11).

Case III. - In this case, there is more than one junction as illustrated in figure 3. The outflow lines from each pair of the two pairs of tanks are joined to form two common junctions. The common lines from these junctions are then joined to give a single line crossing the system boundary.

The mass flow rate in each of the two common lines is $\dot{m}_k$. The total mass flow rate is the sum of these individual flow rates.

$$\dot{m}_T = \sum_{k=1}^{2} \dot{m}_k \tag{17}$$

The upper limit on the range of k would increase if there were more than two common lines. The flow rate in each of the common lines is the sum of the flow rates for each of the tank outflow lines leading to the common line. Thus

$$\dot{m}_{k=1} = \sum_{j=1}^{2} \dot{w}_j$$

and

$$\dot{m}_{k=2} = \sum_{j=3}^{4} \dot{w}_j \tag{18}$$

If the outflow lines are arranged differently, then the summing index would, of course, be changed.

The total pressure at a nearby point downstream of the k^{th} junction in terms of the losses in the j^{th} outflow line is

$$P_k = P_{oj} + \rho g(y_j + h_{jk}) - \left(\frac{4fL}{D} + K + K'\right)_{jk} \frac{V_{jk}^2 \rho}{2} \tag{19}$$

The total pressure at a nearby point downstream of the final junction (c) is

$$P_c = P_k + \rho g h_{kc} - \left(\frac{4fL}{D} + K + K'\right)_{kc} \frac{V_{kc}^2 \rho}{2} \tag{20}$$

Equations (17) through (20) are used to find the mass flow rates from each of the tanks.

Solution of Equations

For each of these example cases, there are enough equations to solve for the unknowns in the system. The initial height of liquid in each tank is a known starting condition. Therefore, the simultaneous differential equations are solved directly to find the height of the liquid in each tank as a function of time. The algebraic equations determine the individual flow rates and pressures throughout the system.

A fourth order Runge-Kutta form of numerical integration is used to solve the differential equations. Because the coupling equations are nonlinear, an iterative procedure was used to find the junction pressures for each evaluation of the differential equations.

EXPERIMENTAL APPARATUS AND INSTRUMENTATION

The water outflow test facility, as shown in figure 4, was constructed with four 32-inch (0.81 m) diameter plexiglass spheres each of which had a sump attached to the lower half. Each tank had a liquid volume of approximately 74 gallons (0.28 m^3). Stainless steel tubing was used for the outflow lines and the crossflow lines that interconnected the four sumps. The outflow lines from each tank were joined at the center of the four-tank configuration into a common 2.0 inch (5.08 cm) nominal diameter copper tube connected to a centrifugal pump. The outlet side of the pump was fed into three interconnected reservoir tanks as shown in figure 5.

Total outflow from the four spheres was controlled by a ball valve located on the outlet side of the pump. This allowed the flow rate to be varied between 0 and approximately 16.7 pounds per second (7.57 kg/sec) or 120 gallons per minute (0.0076 m^3/sec). In addition, a valving arrangement on the outlet and inlet sides of the pump permitted filling of the test tanks through the outflow lines. Ball valves were also installed in each of the outflow and crossflow lines to provide a means for isolating each tank from the other for the simulation of initial unsymmetrical loading conditions. Cruciform antivortex baffles were provided at the sump inlets.

Instrumentation consisted of a flowmeter located in the 2.0 inch (5.08 cm) diameter pump inlet line to measure total flow rate and a float system on each tank that monitored the liquid level in the tank. The float system, as seen in figure 4, consisted of a polystyrene float connected to a rotating potentiometer through a pulley arrangement. Output from the potentiometer was fed into a recording oscillograph so that the liquid level was constantly recorded during the outflow period.

PROCEDURE

All tanks were initially calibrated to convert oscillograph trace displacement to liquid volume in each tank. Checkpoints were established and recorded each day before and after the experimental runs.

The tanks were initially filled either to equal or unequal levels depending on the desired conditions and then outflowed at a predetermined flow rate for each run. Outflow was terminated just prior to the instant the float in the lowest liquid level tank struck the antivortex baffle. This usually resulted in approximately 4 to 6 pints (0.0019 to (0.0028 m^3) remaining in the lowest residual tank. This did not include the liquid remaining in the sump.

Data was reduced by converting chart deflection to liquid volume remaining in each tank. The tank with the lowest final liquid level was taken as reference, and its residual volume was subtracted from the residual volume in each tank to obtain the true residual. The true residual in the reference tank was therefore zero, and it was assumed that the true residuals in the remaining three tanks were valid for the condition of zero residual in the reference tank. The volumetric residuals were then reduced to percentages of the total liquid volume of the four tanks which was approximately 296 gallons (1.120 m^3).

It was possible to read the position of the oscillograph trace corresponding to the liquid level in a particular tank with an accuracy of about ±0.02 inch (0.051 cm). Therefore, liquid residual volumes could be determined with an accuracy of approximately ±0.264 gallons (0.001 m^3) below 2.64 gallons (0.01 m^3) and ±0.528 gallons (0.002 m^3) above 2.64 gallons (0.01 m^3). The difference in accuracy was due to the nonlinear relation between vertical height (float movement) and segment volume for a sphere. At low liquid levels, it was possible to change the gage factor so that full-scale chart deflection corresponded to one-fourth the tank volume thereby improving the accuracy by a factor of four.

RESULTS AND DISCUSSION

Four Tanks With Equal Length Outflow Lines

Figure 6 is a schematic of a system of four tanks with equal length outflow lines. The sumps in this case were 8.0 inch (20.3 cm) diameter cylindrical sumps. The outflow lines were extended up through the sumps with the inlets approximately at the tank bottoms so that equalizing crossflow was isolated from outflow. Each tank was interconnected with its adjacent tanks through crossflow lines. The common junction point of the outflow lines was centrally located and was below the level of the sumps.

Figure 7 is a bar graph representing the liquid residual remaining in each tank when the tanks were outflowed from equal initial full levels with the crossflow line valves open and closed. Analytically, the outflow from each tank passes through an identical path so that the predicted residual for each tank was zero for all flow rates with the crossflow lines open and closed. Experimentally though, the total residual with crossflow lines closed and with a flow rate of 13.9 pounds per second (6.31 kg/sec) or 100 gallons per minute (0.0063 m^3/sec) amounted to 0.33 percent of the four-tank volume. This small residual can be attributed to the nonsymmetry of the system caused by manufacturing tolerances. The total residual was reduced to 0.03 percent when the crossflow lines were opened.

Figures 8 and 9 show the analytical and experimental residuals as a function of flow rate. These residuals were a result of unsymmetrical liquid loading at the beginning of the outflow run. The crossflow lines were open for each flow rate. Tank 3 was always initially full, and the remaining three tanks were initially filled to equal levels of 50 percent full in one case and 20 percent full in the other. Tank 1, which was diagonally opposite the full tank, always emptied first.

Figure 8 is a comparison of the analytic and experimental residual in the initially full tank which always contained the greatest residual. Tanks 2 and 4, which were adjacent to the full tank, resulted in the same analytic residual because of symmetry. The analytic and experimental data for these two tanks are shown in figure 9. The experimental data represent the average of the residuals in tanks 2 and 4 since there were small differences in the two residuals. It can be seen from figures 8 and 9 that for each unsymmetrical loading condition there is a flow rate below which the tanks are equilibrated; and, hence, zero residuals are achieved. As the initial loading becomes more unbalanced, the maximum flow rate below which equilibrium takes place decreases for a constant crossflow line size. Increasing the crossflow line diameter would increase this maximum flow rate.

Figure 10 is the sum of data given in figures 8 and 9 and therefore represents the total residual as a function of flow rate. Three analytic curves are given for each unsymmetric loading condition. The two outer curves represent a 50 percent deviation in the crossflow line loss coefficient from that used to generate the central curve (K_{ij}), which was obtained using the loss coefficients given in reference 5. The variation is shown because the results of reference 6 demonstrate that the loss coefficients can vary considerably from their nominal values; and as seen in figure 10, these variations have a minor effect on the analytical results which does not materially alter the good agreement with experimental data.

Four Tanks With Unequal Length Outflow Lines

The previous configuration used bottom drained tanks with equal length outflow lines that were joined at the center of the four-tank arrangement. Interference between a centrally located engine and the outflow piping could require mounting the engine aft of the tank bottoms. A schematic of a four-tank system with outflow lines joined at a point other than the configuration center is shown in figure 11. This configuration would allow a central engine located forward of the tank bottoms. Joining the outflow lines at some point other than the center requires unequal length outflow lines.

The bar graph of figure 12 represents the percent residual remaining in each tank for three crossflow line conditions. The tanks were initially symmetrically loaded, and the flow rate was 13.9 pounds per second (6.31 kg/sec) or 100 gallons per minute (0.0063 m^3/sec). The residuals in tanks 3 and 4 which had the longer outflow lines amounted to approximately 3.5 percent in each when all the tanks were outflowed from an initial full level and the crossflow lines were closed. Residuals in these tanks were reduced by a factor of six when the crossflow lines were open. Further reduction in residuals was accomplished by increasing the crossflow line size between tanks 1 and 4 and between tanks 2 and 3 from 0.875 inch (2.22 cm) inside diameter to 1.375 inch (3.49 cm) inside diameter.

Figure 13 shows the effect of flow rate on the total residual in the two tanks with the long outflow lines (tanks 3 and 4). The experimental data for this figure were obtained using 0.875 inch (2.22 cm) inside diameter tubing for the crossflow lines between all tanks. Symmetry of the system permitted data to be taken with two tanks only so that the flow rate range could be extended beyond that available with the four-tank system. Data comparison indicated that within the accuracy of the data, the residuals obtained when outflowing four tanks at a given flow rate were equivalent to those obtained when outflowing two tanks at one-half of this flow rate. The two tanks used in this particular case were tank 1 which had a short outflow line and tank 4 which had a long outflow line. Validity of substituting two-tank data for four-tank data (by doubling the residuals obtained with two tanks outflowing at one-half the four-tank outflow rate) is shown in figure 13 at 7.0 pounds per second (3.18 kg/sec) or 50.4 gallons per minute (0.0032 m^3/sec) with the crossflow lines closed. The two-tank data near this point represents twice the percent residual obtained when outflowing tanks 1 and 4 at 3.6 pounds per second (1.63 kg/sec) or 25.9 gallons per minute (0.0016 m^3/sec). It can be seen that both the four-and two-tank data compare rather well with the analytical curve.

With the crossflow lines closed, both the analytical and experimental residuals are rather substantial even though they tend to level off above 13.9 pounds per second (6.31 kg/sec) or 100 gallons per minute (0.0063 m^3/sec). Even with the crossflow lines open, a significant residual is obtained at high flow rates.

Figure 14 shows a comparison of analytic and experimental residuals as a function of the degree of nonsymmetry in the initial loading of the tanks. One of the tanks with a long outflow line (tank 3) was filled completely while each of the other three had a prescribed equal liquid volume as indicated by the abscissa of the graph in figure 14. The flow rate was maintained at 13.9 pounds per second (6.31 kg/sec) or 100 gallons per minute (0.0063 m^3/sec), and the crossflow lines were open for all the experimental runs. It can be seen that with 80 percent or more liquid in each of the three partially filled tanks, the total residual, which is the sum of the individual tank residuals, is approximately 1 percent. As the initial amount of liquid in the three tanks decreases, the residual in the initially full tank increases rapidly. At the 100 percent full point, which corresponds to having all the tanks initially full, the total experimental residual is 1.15 percent which agrees with figure 13 at 13.9 pounds per second (6.31 kg/sec) or 100 gallons per minute (0.0063 m^3/sec) when the lines are open.

Four Tanks With Equal Length Dip Tube Outflow Lines

The configuration photographed in figure 15 and shown schematically in figure 16 is similar to the first configuration discussed except that the outflow lines penetrate the top of the tank rather than the bottom. An arrangement such as this allows the engine pump inlet to be forward of the tank bottoms and still maintains equal length outflow lines. Both the outflow and crossflow lines for this configuration were 1.25 inch (3.18 cm) stainless steel tubing with an inside diameter of 1.125 inches (2.86 cm). The dip tube in each tank had a contoured inlet as shown in figure 16 to help streamline flow into the dip tube entrance.

The sumps attached to the bottom of the tanks in this configuration were more representative of those that would likely to be used on flight type tanks. Figure 17 shows the 6.5 inch (16.5 cm) inside diameter hemispherical sump used for the experimental testing. The inner surface was a hemisphere whereas the outside surface was made cylindrical for fabrication convenience. Normally, both the inside and outside surfaces would be hemispherical.

Figure 18 shows the effect of dip tube inlet height on the total residual in the tanks. The height of the dip tube inlet was measured from the bottom of the inner surface of the sump. All four tanks were filled to equal full levels and outflowed at a flow rate of 16.4 pounds per second (7.44 kg/sec) or 118 gallons per minute (0.0074 m^3/sec). The curve of figure 18 is a result of the experimental data and does not represent an analytical prediction. It is apparent from this figure that the total residual in the tanks decreases as the dip tube inlet height is increased to a point that is approximately equal to the entrance diameter of the crossflow lines which were tangent to the sump inside surface. Beyond this point, the residual remains constant. The crossflow line entrance in this case is 1.125 inches (2.86 cm) in diameter. The increase in residual as the dip tube height decreases is caused by coupling of the flow between the crossflow lines and the outflow lines. It can be seen that a dip tube inlet height that is approximately equal to or greater than the crossflow line diameter served to decouple the flows.

It should be noted that the residual is based on the liquid remaining in the tanks and does not include the liquid in the sumps. Since the liquid can only be outflowed from the tanks as long as the dip tube inlet is below the liquid level, it is important to keep the dip tube inlet within the sump where the total volume is small. Obviously, if the dip tube inlet is set at a level above the sump inlet, the residual in the tanks will increase rapidly. Therefore, the dip tube height for the experimental runs was set at 3.25 inches (8.25 cm).

Figure 19 shows the total residual as a function of the initial amount of liquid in three tanks. Tank 3 was initially full and each of the other three tanks were partially filled to the liquid volume indicated along the abscissa. Very little equilibration takes place with the crossflow lines closed. When the crossflow lines are open, equilibration takes place when the liquid volume in each of tanks 1, 2, and 4 is 50 percent or more. Below this point, the total residual increases rapidly. In the analysis for this case, it was assumed that the head loss in each line due to mixing at the junction was equal to the velocity head in the line. An alternate assumption could have been that there was no head loss due to mixing. Figure 19 illustrates the effect of both of these assumptions, and it can be seen that there is little difference in the two curves.

Figure 20 represents a comparison of experimental and analytical data during a complete outflow phase of the dip tube configuration. The tanks were initially off-loaded so that tank 3 contained 72 percent liquid, and each of the other three tanks was 13 percent full. Flow rate was kept constant at 2.22 pounds per second (1.01 kg/sec) or 16 gallons per minute (0.001 m^3/sec) for the first 14 seconds of the cycle and then increased to 7.65 pounds per second (3.47 kg/sec) or 55 gallons per minute (0.0035 m^3/sec) for the remainder of the cycle. This was done to simulate an idle or low thrust condition prior to full thrust operation. The idle operation's primary purpose is to allow conditioning of the turbomachinery, and it normally requires a relatively low outflow rate. Hence, time is provided for liquid equalization flow through the crossflow lines before the full thrust outflow rate is initiated.

Only the amount of liquid in the fullest tank and the one diagonally opposite it are shown. The other two tanks have curves almost identical to the lower liquid level tank. Therefore, they have not been included on the graph. It can be seen that all tanks empty at the same time and that there is good correlation between the analytic and experimental data throughout the entire outflow period.

CONCLUSIONS

1. Crossflow lines will generally be necessary for reducing residuals to an acceptable level when outflowing multiple tanks through a common discharge line.

2. By selecting the proper crossflow line size, all three of the configurations investigated can be designed to function as acceptable low residual propellant systems. For a minimum length stage employing multiple tanks with the engine pump inlet forward of the tank bottoms, the equal length dip tube outflow line configuration is most desirable because line length is kept at a minimum.

3. Based on experimental data for the hemispherical sumps discussed herein, a dip tube inlet height (above the bottom of the sump) that is equal to or greater than the crossflow line diameter is adequate to avoid coupling between the crossflow and outflow of the liquid.

4. The analysis adequately predicted the liquid residuals in each tank as a function of time and accurately predicted the point at which crossflow lines ceased to be completely effective in equilibrating the liquid imbalances. The analysis also provides a means of determining the crossflow line size required for equilibration when the fluid is initially unequally distributed.

Lewis Research Center,
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128-06-04-02-22.

APPENDIX A

SYMBOLS

A cross sectional area

a fluid acceleration

D inside diameter of pipe

f Fanning friction factor

g acceleration due to gravity or thrust

H head loss of fluid

h difference in elevation

K loss coefficient due to "minor" losses (exits, entrances, fittings, etc.)

K' loss coefficient due to mixing

L total length of tube

M number of tanks

m mass of fluid in tank

$\dot{m}$ mass rate of flow of fluid

N number of crossflow lines

P pressure

$\mathscr{P}$ wetted perimeter

Q number of outflow lines

r radius of tank

S length along line

t time

V velocity

v volume of liquid

$\dot{w}$ mass rate of flow through tank outflow line

y liquid height in tank

θ angle centerline of tube makes with the normal to the acceleration vector

ρ liquid mass density

τ wall shear stress

Subscripts:

c denotes last junction in system

i denotes a propellant tank

j denotes a propellant tank

k denotes first junction of lines from propellant tanks

o refers to liquid surface in propellant tank

T refers to total flow rate from system

$1,2$ refers to points along flow line

APPENDIX B

APPLICABILITY OF ANALYSIS TO A HYPOTHETICAL FLIGHT VEHICLE

The purpose of the analysis is to predict the hydraulic behavior of a multitank fuel or oxidizer system for flight vehicles. A prime area of interest is in the behavior of the propellant during the later firings of a multi-burn mission. Prior to the initial firing, each of the tanks would be full; and no significant imbalance should occur for symmetrical outflow lines during the first firing. To illustrate the applicability of the analysis to a flight vehicle, a hypothetical liquid oxygen system utilizing four identical spherical tanks is presented. A schematic of an upper stage which contains this system is shown in figure 21. The pertinent characteristics of the liquid oxygen system as well as the overall stage are as follows:

Diameter of each oxidizer tank, in. (m)	42 (1.068)
Total oxidizer flow rate, lb/sec (kg/sec)	28.3 (12.84)
Oxidizer tank pressure, psia (N/m^2)	20 (1.379×10^5)
Propellant density, lb/ft^3 (kg/m^3)	70.6 (1.130×10^3)
Ratio of ozidizer weight to fuel weight	5
Second-burn firing time, sec	69.7
Thrust, lb (N)	15 000 (6.67×10^4)
Initial total weight at second burn, lb (kg)	6 000 (2 720)
Final total weight, lb (kg)	3 640 (1 650)

Each outflow line is made from 1.25 inch (3.18 cm) inside diameter tubing and is 80 inches (2.03 m) long. The crossflow lines are 45 inches (1.14 m) long. It is assumed that each outflow and crossflow line has a loss coefficient of 1.5 and a pipe roughness corresponding to that for drawn tubing.

For this example, it is assumed that prior to second ignition the total liquid in the system is equal to 31.5 percent of the four-tank volume. In addition, it is assumed that the maximum liquid imbalance in the system occurs when one tank becomes completely filled by liquid migration and the remaining liquid is evenly distributed between the other three tanks. Hence, each of these tanks is 8.67 percent full. Figure 22 illustrates the equilibrium performance of this system as a function of the degree of liquid imbalance in the four-tank system. The time for the system to equilibrate (when the analytical residuals of the four tanks are within ±0.01 percent of each other) is given as a function of the amount of liquid in the fullest tank for four different crossflow line sizes. Equilibration time can be determined from the figure for various combinations of crossflow line size and system initial liquid imbalance. For example, if the fullest tank contains 66 percent liquid at the time of the second ignition, then each of the other tanks is 20 percent full and the time to equilibrate measured from ignition start is 48 seconds if 1.625 inch (4.13 cm) inside diameter crossflow lines are used.

Each tank must initially have some liquid in it to prevent blow-through before equilibration can take place. There are various means of insuring that at least some liquid remains in each tank. Several ways of achieving this are discussed in reference 7. Therefore, while it is theoretically possible that no liquid would be in one or more tanks at the beginning of the second firing, measures could be taken to have this possibility highly unlikely.

Figure 22 shows that increasing the crossflow line size permits a given imbalance to equilibrate in a shorter period of time. Alternately, a larger imbalance can be equilibrated in a given time period by using larger diameter crossflow lines. Large crossflow lines are advantageous from an equilibration standpoint, but the larger the line, the greater the weight penalty. This penalty not only includes the weight of the lines themselves, but also the fluid that remains trapped within them. The size of the crossflow lines is determined by the maximum degree of imbalance expected and the desired time for equilibration. The maximum time for equilibration is determined by the duration of the firing.

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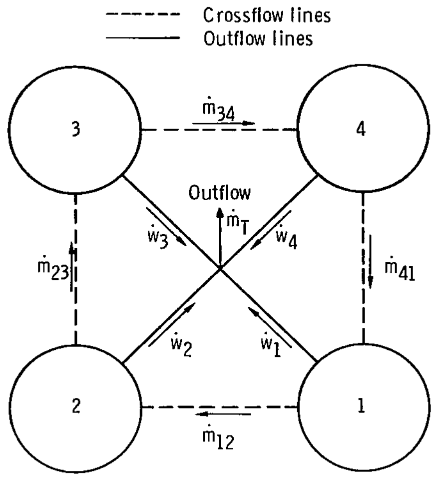


Figure 1. - Schematic of interconnected four-tank system with joined outflow lines from all four tanks.

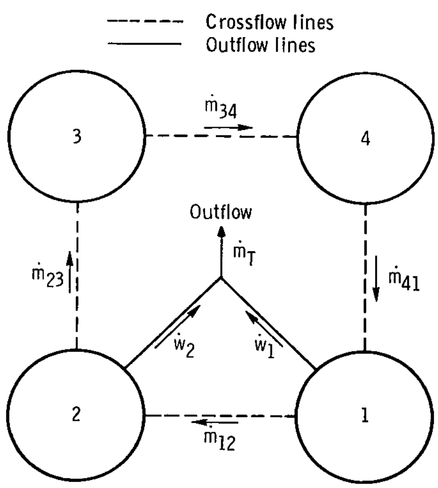


Figure 2. - Schematic of interconnected four-tank system with joined outflow lines from two tanks only.

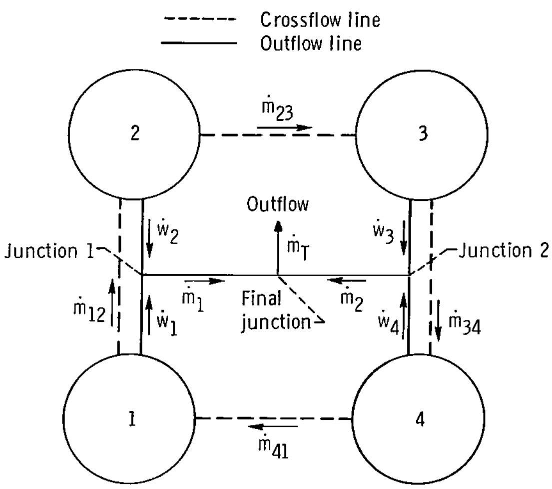


Figure 3. - Schematic of interconnected four-tank system with multiply joined outflow lines.

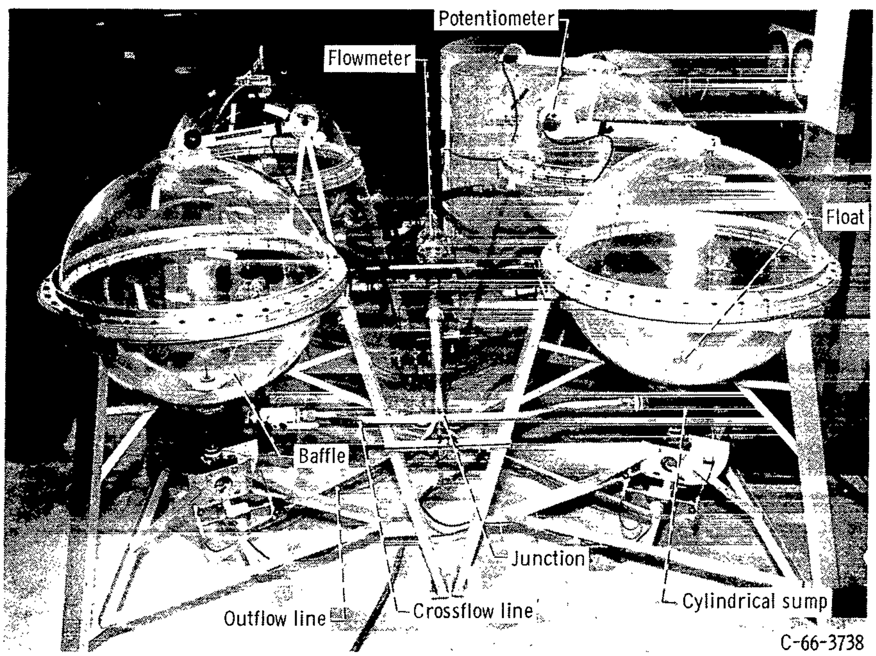


Figure 4. - Four-sphere, symmetrical-outflow-line configuration.

Figure 5. - View of water rig showing reservoir tanks and motor-driven pump.

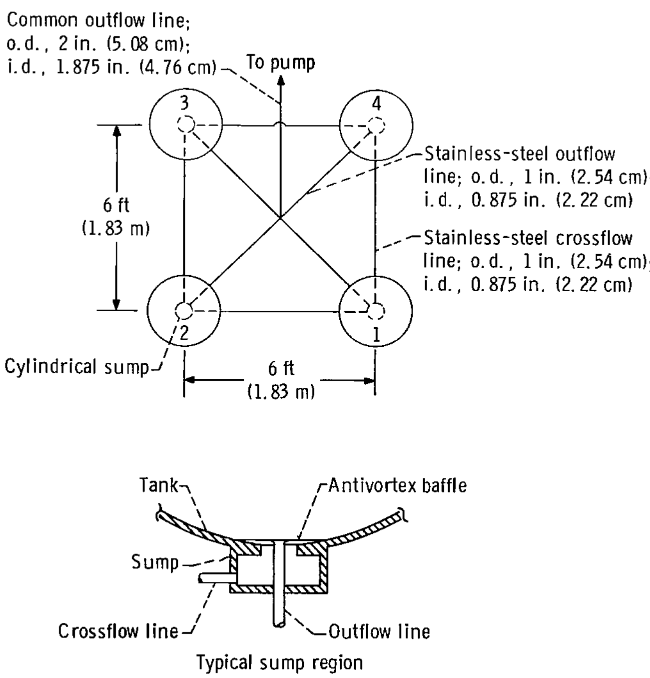


Figure 6. - Four tanks with equal-length outflow lines.

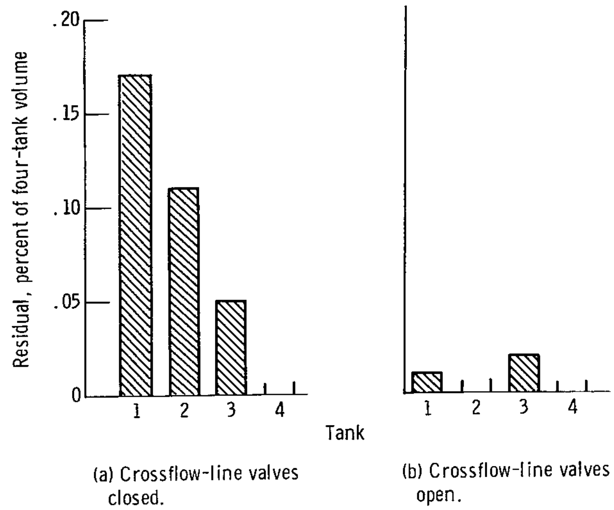


Figure 7. - Final residuals for four tanks with equal-length outflow lines. Outflow rate, 13.9 pounds per second (6.31 kg/sec).

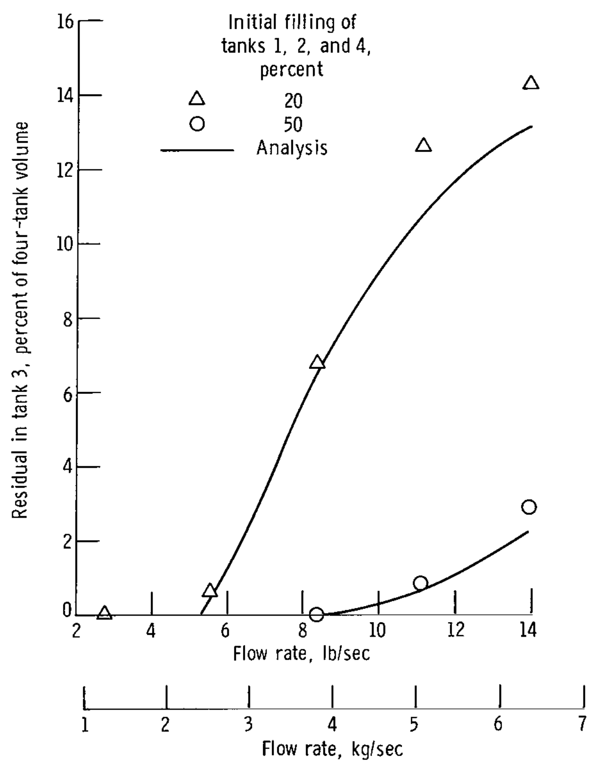


Figure 8. - Residual in the full tank (tank 3) of the equal length outflow line system as function of flow rate for two different initial conditions. Crossflow lines open.

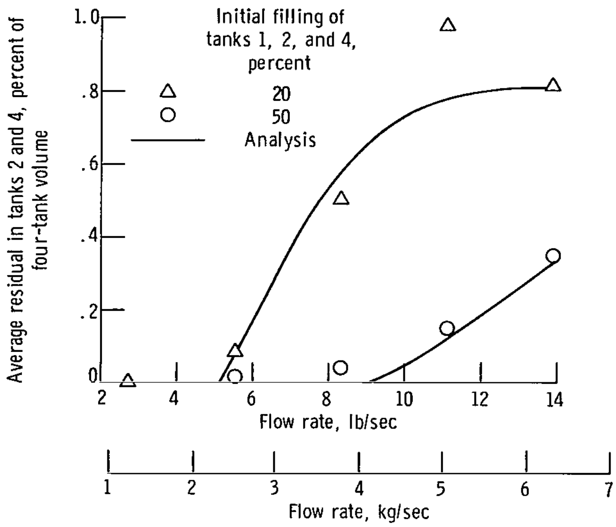


Figure 9. - Residual in each of tanks 2 and 4 of the equal length outflow line system as function of flow rate for two different initial conditions. Crossflow lines open; tank 3 initially full.

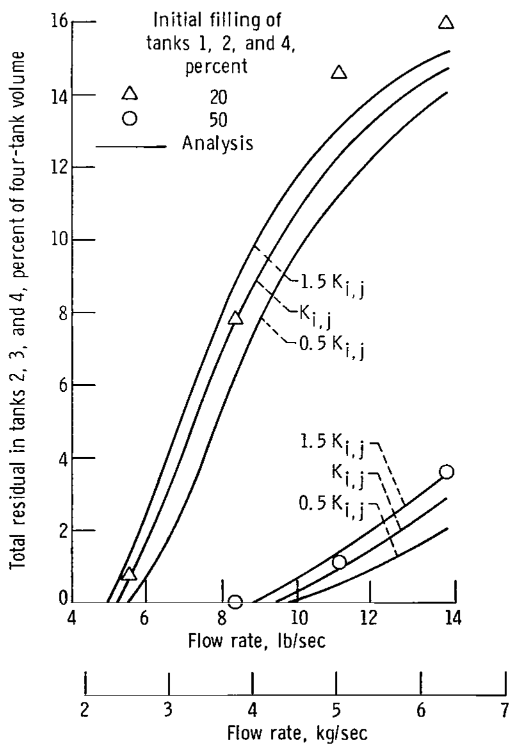


Figure 10. - Effect of crossflow-line loss coefficient on total residual of the equal length outflow line system for two different initial conditions. Crossflow lines open; tank 3 initially full.

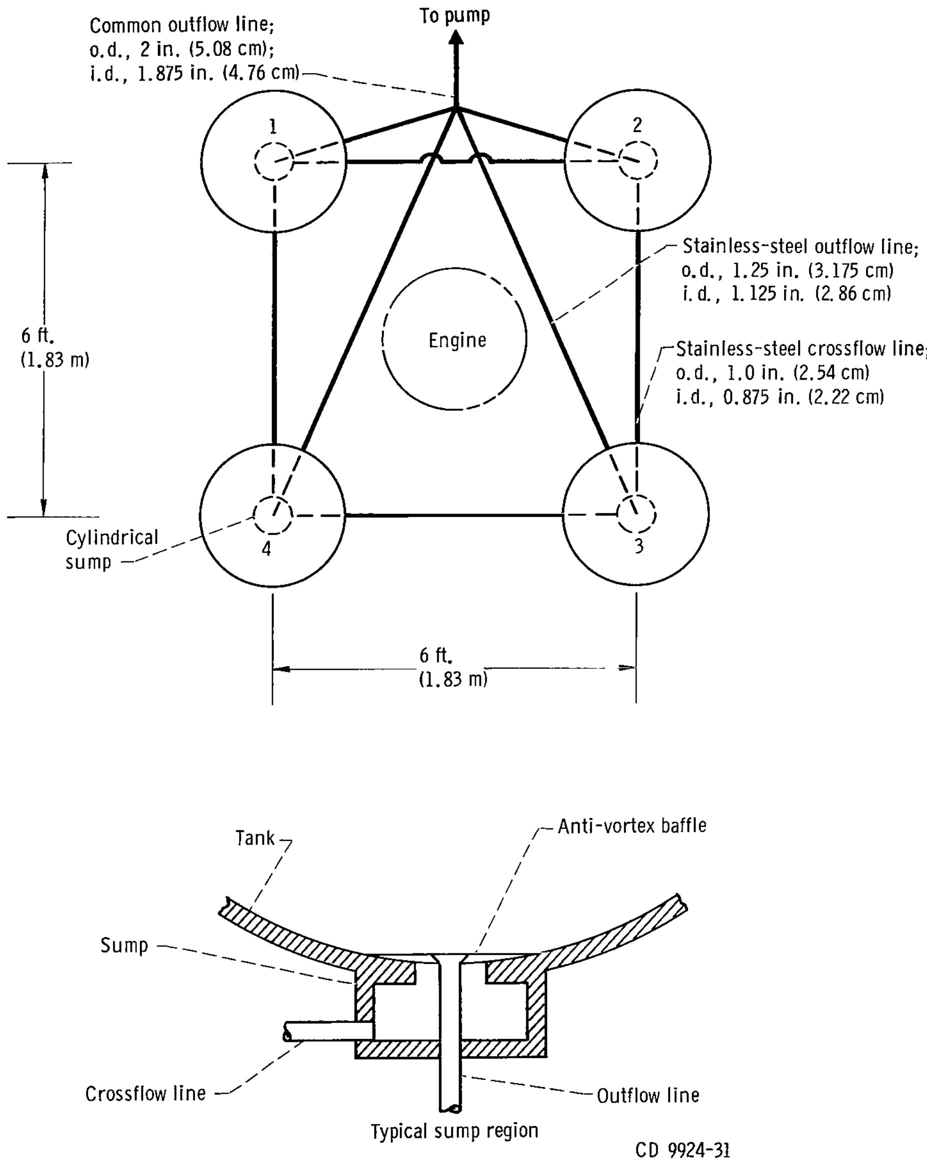
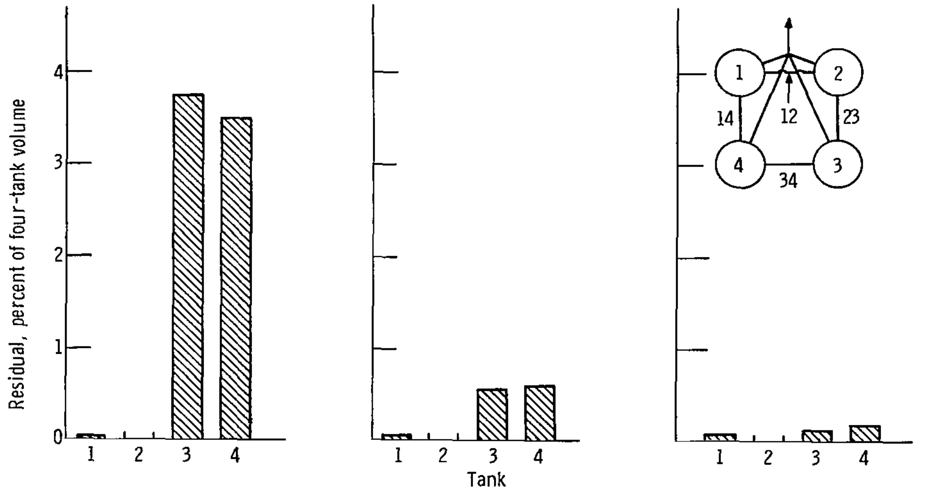


Figure 11. - Four tanks with unequal-length outflow lines.



(a) Crossflow-line valves closed.

(b) Crossflow-line valves open. All crossflow lines: o.d., 1 inch (2.54 cm); i.d., 0.875 inch (2.22 cm).

(c) Crossflow-line valves open. Crossflow lines 12 and 34: o.d., 1 inch (2.54 cm); i.d., 0.875 inch (2.22 cm). Crossflow lines 14 and 23: o.d., 1.5 inches (3.81 cm); i.d., 1.375 inches (3.49 cm).

Figure 12. - Final residuals for four tanks with unequal-length outflow lines. Outflow rate, 13.9 pounds per second (6.31 kg/sec).

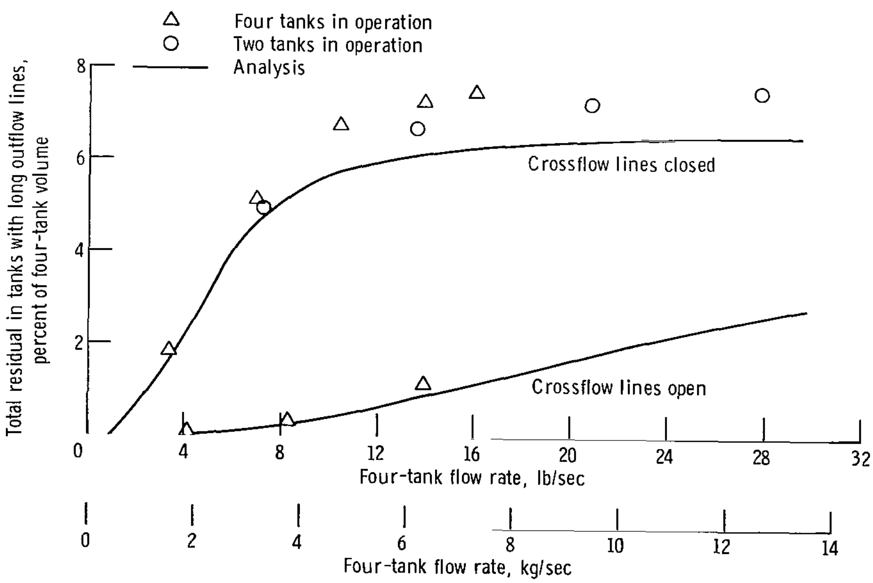


Figure 13. - Total residual in tanks with longer outflow lines as function of flow rate. Crossflow-line inside diameter, 0.875 inch (2.22 cm).

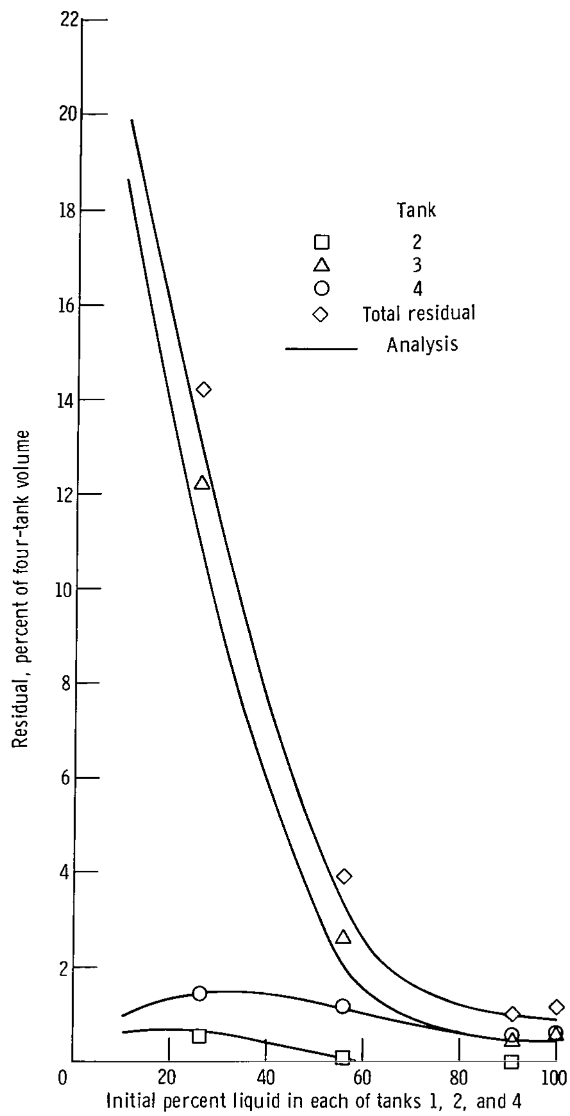


Figure 14. - Residuals in tanks 2, 3, and 4 as functions of initial amount of liquid in each tank. Tank 3 initially full; unequal-length outflow lines; crossflow lines open; outflow rate, 13.9 pounds per second (6.31 kg/sec); crossflow-line inside diameter, 0.875 inch (2.22 cm).

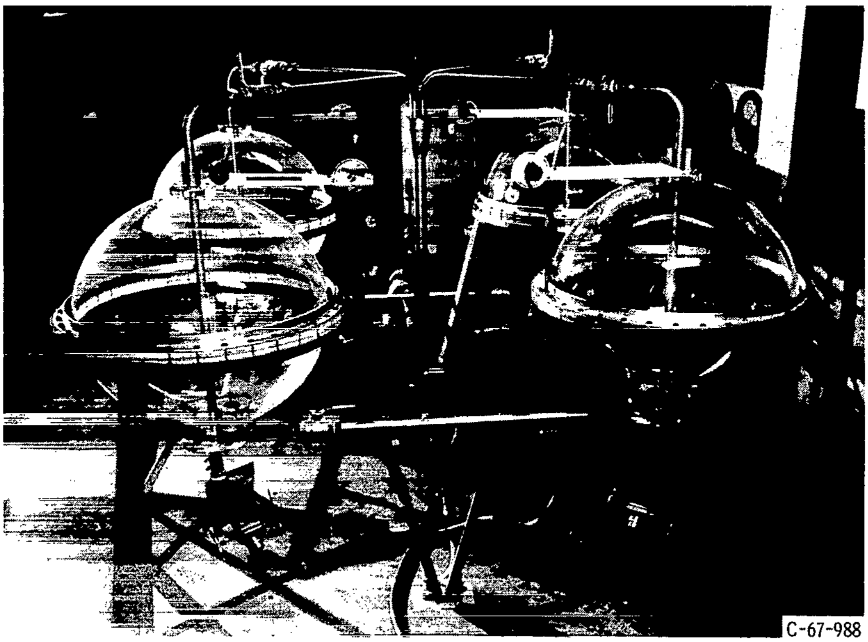


Figure 15. - Four-sphere symmetrical-dip-tube outflow line configuration.

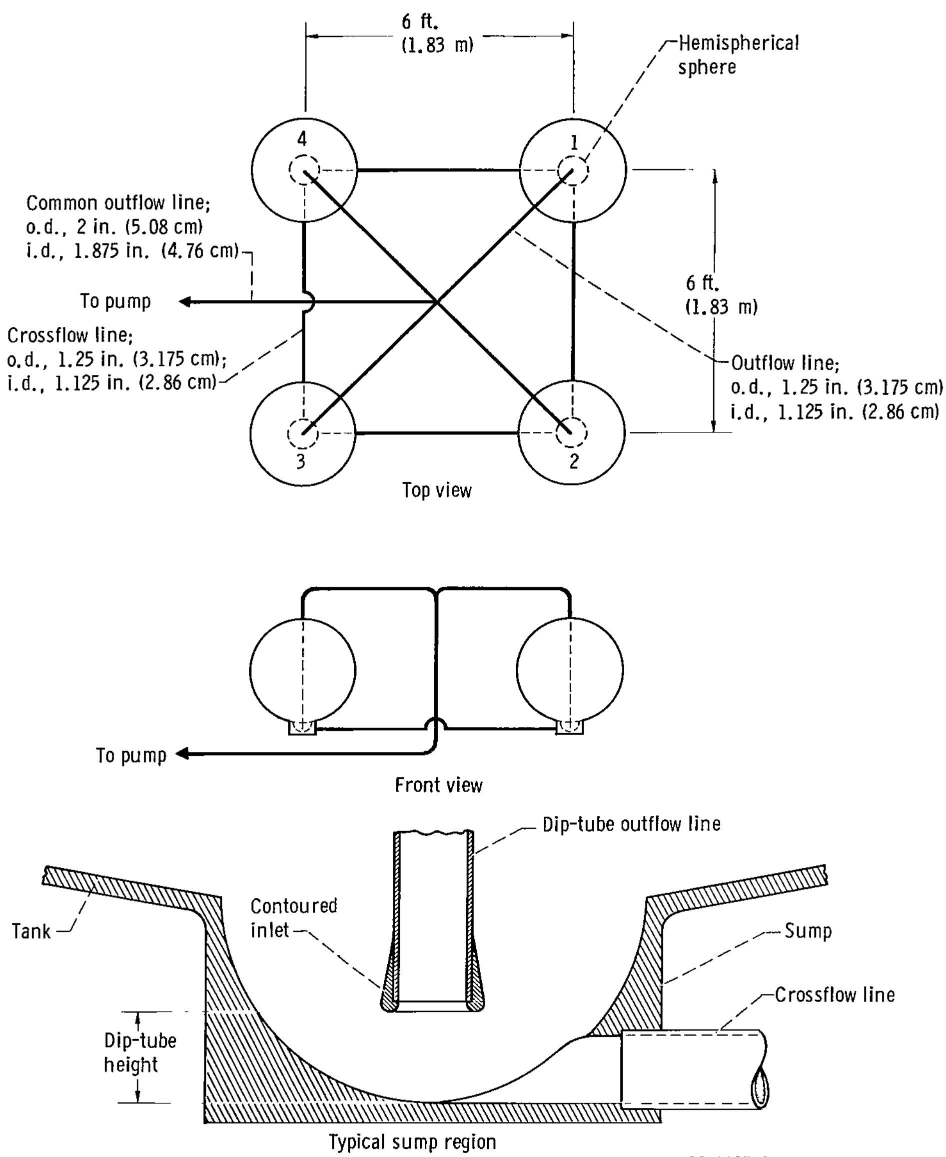


Figure 16. - Four tanks with equal-lenght dip-tube outflow lines.

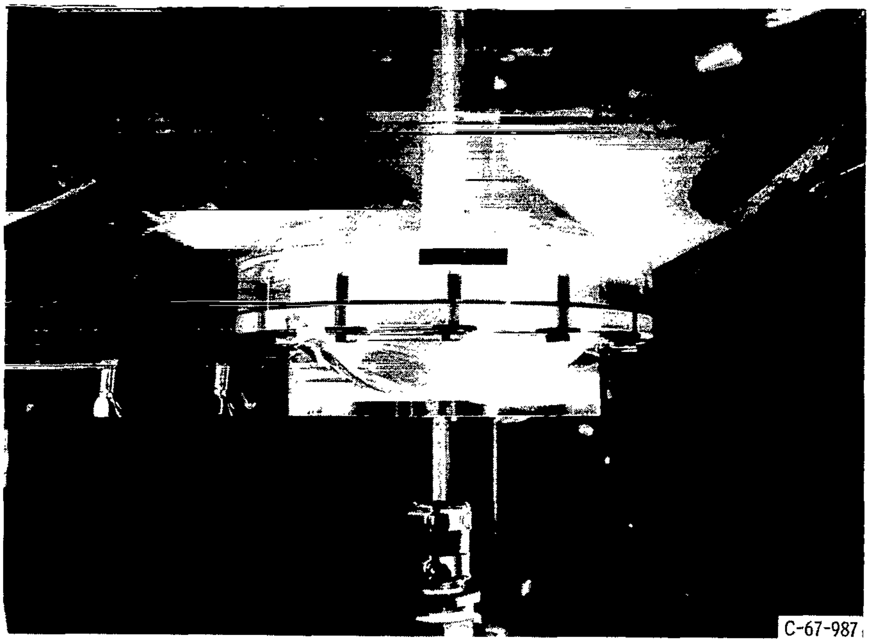


Figure 17. - View of dip-tube configuration showing hemispherical sump and crossflow line.

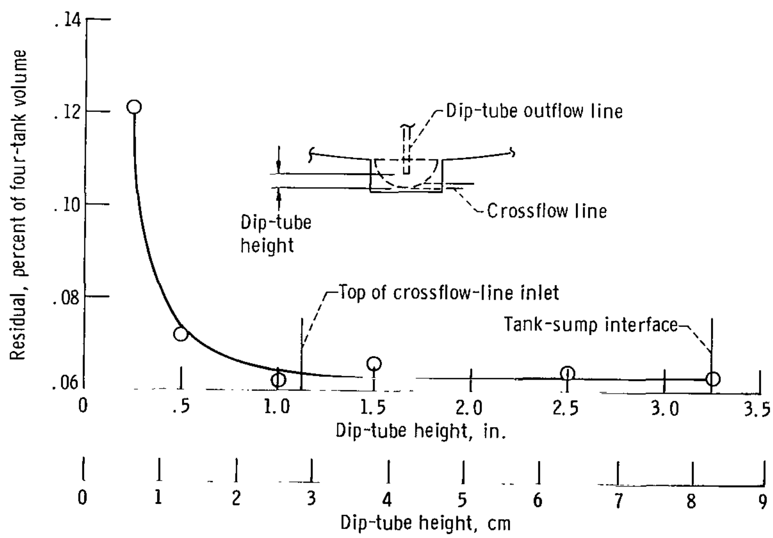


Figure 18. - Experimental total residual as function of dip-tube height. All tanks initially full; crossflow lines open; outflow rate, 16.4 pounds per second (7.44 kg/sec).

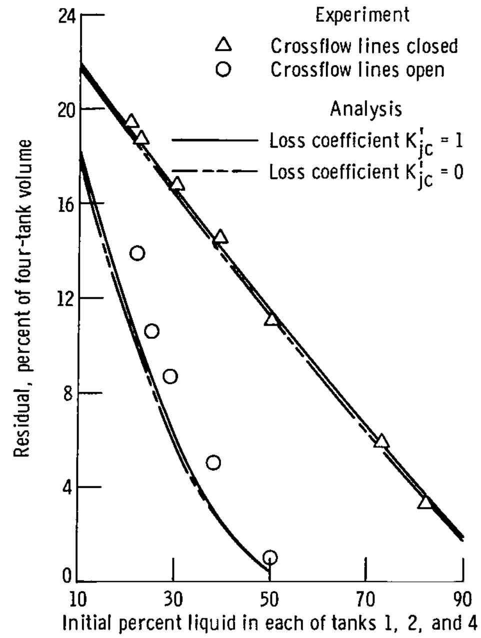


Figure 19. - Total residual as function of initial amount of liquid in each tank. Tank 3 initially full; outflow rate, 16.4 pounds per second (7.44 kg/sec); dip-tube height, 3.25 inches (8.25 cm); crossflow-line inside diameter, 1.125 inches (2.86 cm).

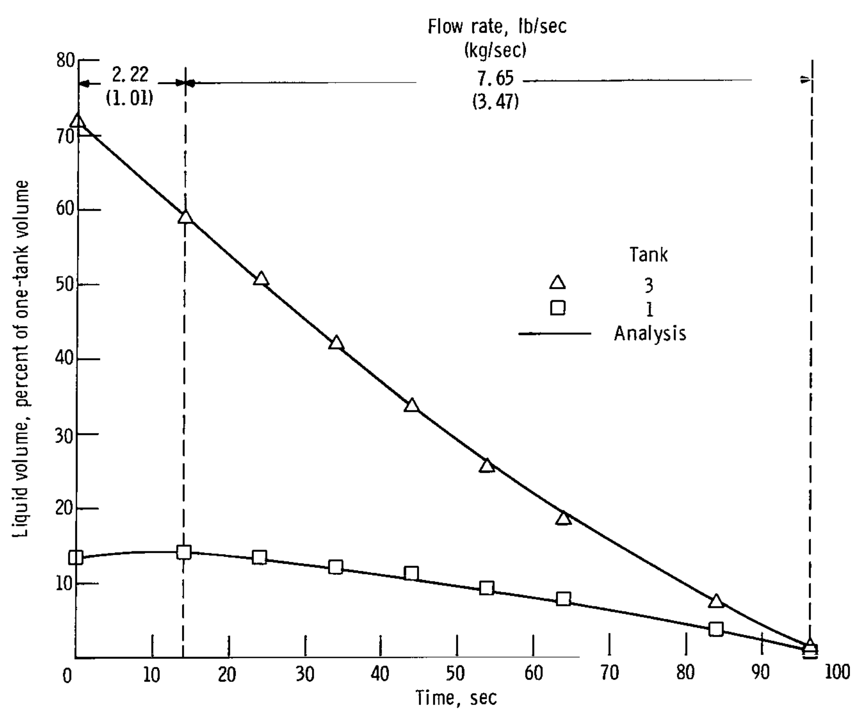


Figure 20. - Percent liquid volume in tanks 1 and 3 as function of time. Crossflow lines open; initial liquid volume in tank 3, 72 percent; initial liquid volume in each of tanks 1, 2, and 4, 13 percent; dip-tube height, 3.25 inches (8.25 cm).

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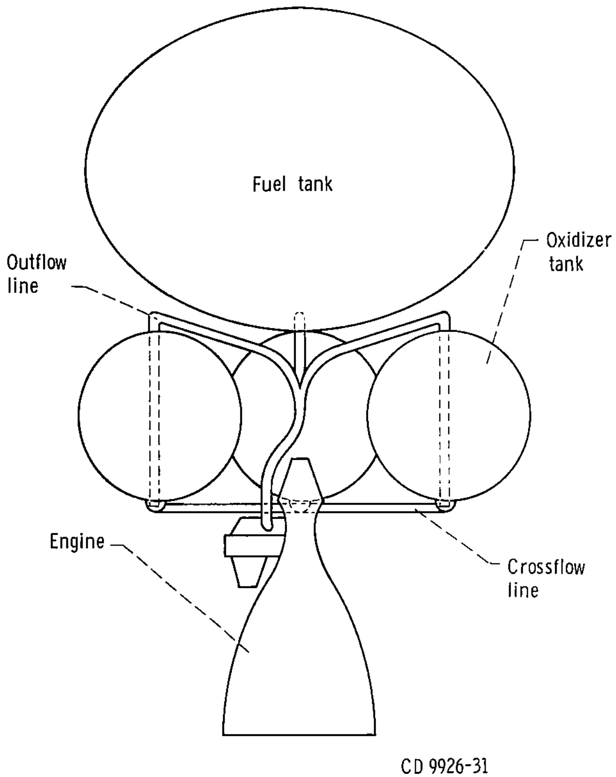

Figure 21. - Hypothetical vehicle propellant storage system.

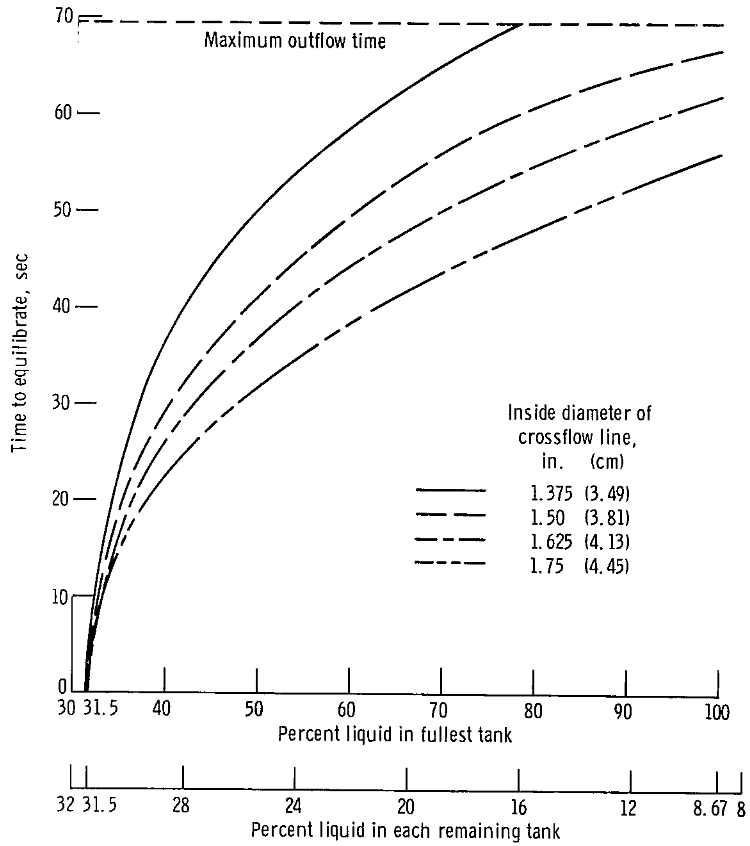

Figure 22. - Time to equilibrate as function of percent liquid in fullest tank and percent liquid in each of the remaining tanks for various crossflow-line sizes in a hypothetical liquid-oxygen system.

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